Design of a Broadband Single-Layer Linearly Polarized Reflectarray Using Four-Arm Spiral Elements

Fei Xue, Hong-Jian Wang, Min Yi, Guang Liu and Xing-chao Dong

***Abstract*—A single-layer broadband reflectarray antenna with four-arm spiral elements is presented. Large range reflection phase has been obtained by varying the length of the arms. The effects of different incident angles on the four-arm element are studied first. Then, a 441-element offset-fed linearly polarized reflectarray is fabricated and measured. The measured results agree well with the simulated results. Measured results show the gain level of 28.35 dB with 1-dB gain bandwidth of 28.7% (12.41-16.31 GHz) and aperture efficiency of 60.2% at center frequency of 13.58 GHz.**

***Index Terms*—Reflectarray, four-arm spiral, broadband, single-layer.**

I. Introduction

A REFLECTARRAY is an antenna which is made up of a planar array with many phasing elements and a feed antenna. As a high gain antenna, reflectarray antennas have many advantages compared to parabolic reflector. such as low cost, low profile and mass, flatness and beam scanning capability [1]. The differential spatial phase delay and the narrow bandwidth of elements are the two factors which limit the bandwidth of a reflectarray [2].

The reflection phase curve of an element is of great importance in design of a reflectarray antenna. In general, element with large range linear reflection phase is necessary for a broadband reflectarray. One of the methods to expand the reflection phase range with lower slope is using multilayer configuration [3]-[5]. About two times 360° reflection phase range was provided by the three-layer element structure in [3] and a 10% bandwidth was achieved by the three-layer reflectarray. The most conspicuous disadvantage of the multilayer structure is the extra manufacture complexity and increased cost. Multi-resonant element can provide more than 360° reflection phase range with less steep for the phase curve [6, 7]. Multi cross loop elements were used to achieve linear reflection phase curve and 30% gain bandwidth for an optimized large size reflectarray was measured in [6]. In addition to multilayer configuration and multi-resonant structure, using aperture couple patches [8, 9] and element with phase delay lines [10, 11] also can achieve large range linear reflection phase. In [11], a broadband element composed of quasi-spiral phase delay lines was proposed to provide about 1000° reflection phase range first. Then, a reflectarray using the element was developed and 16.5% 1-dB gain bandwidth was obtained. In some designs [11, 12], an air layer is added between the substrate and the ground plane in order to obtain a smoother phase curve. However, it will increase the processing error and complexity. Elements with subwavelength lattice period were proposed in [13], and more than 20% 1-dB gain bandwidth was achieved by a single layer reflectarray.

Archimedes spirals have been widely used in the design of different types of antennas [14, 15] except in broadband linearly polarized reflectarray antenna. Using the Archimedes spirals on a broadband linearly polarized reflectarray antenna has not been presented in the previous literature.

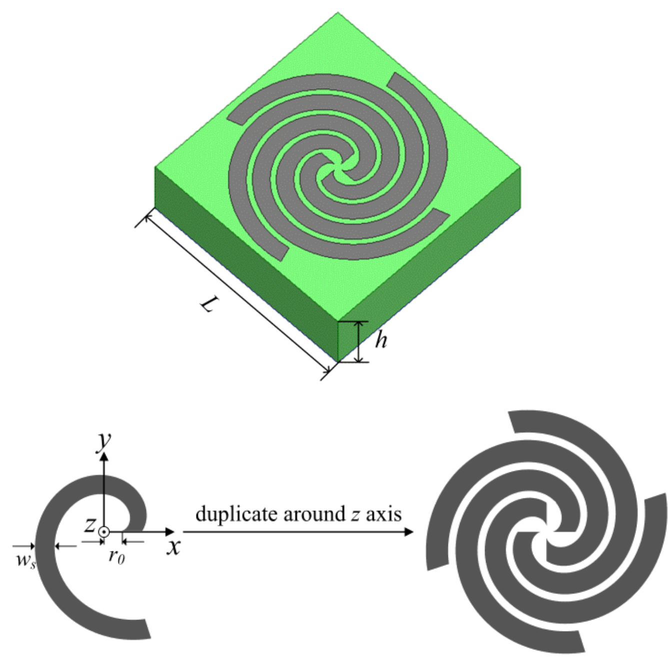

Fig. 1. Geometry of four-arm spiral element.

In this letter, four-arm Archimedes spiral element is optimized to be used as reflectarray cell for wideband linearly polarized operation. About 540° linear reflection phase range

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has been obtained by varying the length of the spiral arms. Based on the four-arm Archimedes spiral element, a single-layer linearly polarized reflectarray is fabricated and tested. The reflectarray is designed to operate in Ku-band and about 28.7% 1-dB gain bandwidth is achieved, which demonstrates excellent broadband performance. Measured results showed the gain level of 28.35 dB and aperture efficiency of 60.2% at center frequency of 13.58 GHz .

II. Element Characteristics

The geometry of the four-arm Archimedes spiral element is shown in Fig. 1. The element is etched on a polyethylene substrate whose relative permittivity is 2.25 and thickness h equals 3 mm. The lattice period of the element L is 10mm, which equals 0.45 wavelengths at the center frequency of 13.58 GHz.

The Archimedes spiral is duplicated around z axis to form the four-arm spiral. In polar coordinates (r,θ) , the Archimedes spiral can be described by the equation $r = r_0 + a\theta$. The parameter r_0 is the starting radius and a controls the distance between successive turns. The length of arms vary with the value of angle θ. By controlling the width of the strips or the distance between successive turns of the Archimedes spiral element, the phase slopes with frequency can be controlled to some extent. The parameters r_0, a and width of the spiral w_s are optimized to obtain large range linear reflection phase curve as the length of the arms varied. The final optimized parameters are selected as follows: r_0 =0.2mm, a =0.6, w_s =0.7 mm.

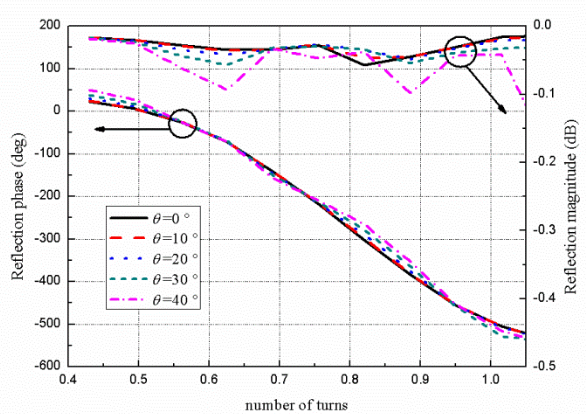


Fig. 2. Reflection phase and magnitude versus number of turns of spiral for different incident angles.

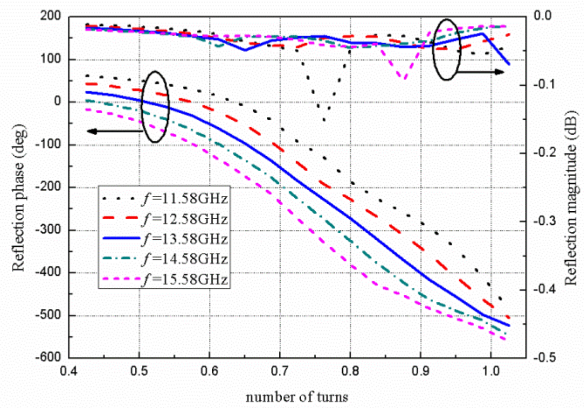
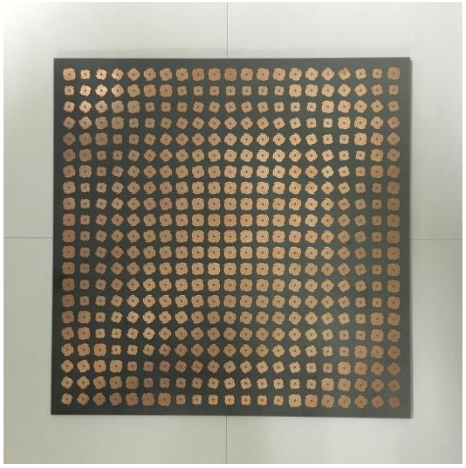


Fig. 3. Reflection phase and magnitude versus number of turns of spiral for different frequencies.

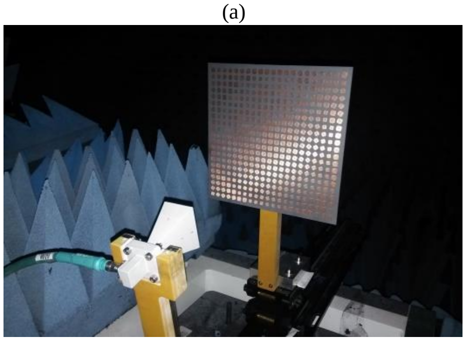
To calculate the reflection phase of the four-arm spiral element, the element structure was analyzed in HFSS and master-slave boundaries with Floquet port are used to model periodic structures. In this paper, the element is excited with a linearly polarized incident plane wave and the reflection phase of the element is obtained by varying the length of the arms. Fig. 2 shows the effect of different incident angles on the reflection phase and magnitude of the element. It can be concluded that the incident angle has little influence on the reflection phase and magnitude curve of the four-arm spiral element. Thus, it is reasonable to use normal incident plane wave for analyzing the elements. The reflection phase and magnitude curves over a wide frequency range of 11.58-15.58GHz are shown in Fig. 3. It is observed that the reflection phase curves at different frequencies have good linearity and in parallel with each other, which indicate the wideband property of the four-spiral element. The reflection magnitude at different frequencies is larger than -0.06 dB.

III. Design Reflectarray and Performance

A 441-element offset-fed linearly polarized reflectarray using the four-arm spiral elements is designed and fabricated. Fig. 4 presents the photograph of the reflectarray antenna prototype. The distance between each adjacent elements is 10 mm which equals 0.45 λ_0 at 13.58 GHz (λ_0 is the wavelength in free space). The focal distance F and aperture D of the proposed reflectarray both are 210mm, which indicates the F/D ratio of 1. The offset angle of the feed antenna is designed as 15 ° with reference to the broadside direction and the main beam points to the mirror direction of the feed offset angle. A pyramidal horn antenna is used as the feed of the reflectarray. The simulated gain of feed horn antenna is 15.2 dB, and the 3-dB beamwidth are 34.5 °and 31.2 °in the E-plane and H-plane, respectively. For further decreasing of the cross-polarization, the elements are arranged in a mirror symmetric configuration by changing the handedness of the spiral arms between the left and right halves of the reflectarray, as shown in Fig. 4(a).



(a)



(b)

Fig. 4. (a) Prototype of the proposed reflectarray antenna. (b) Picture of the reflectarray being tested.

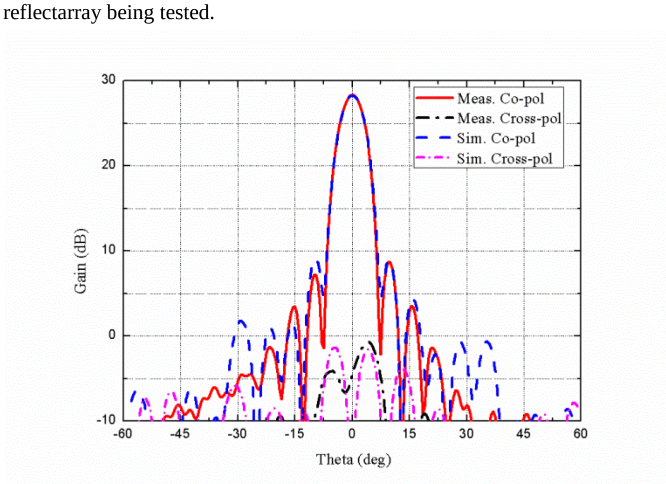


Fig. 5. Measured and simulated radiation patterns of the four-arm spiral element reflectarray for co-polar and cross-polar at 13.58GHz in E-plane.

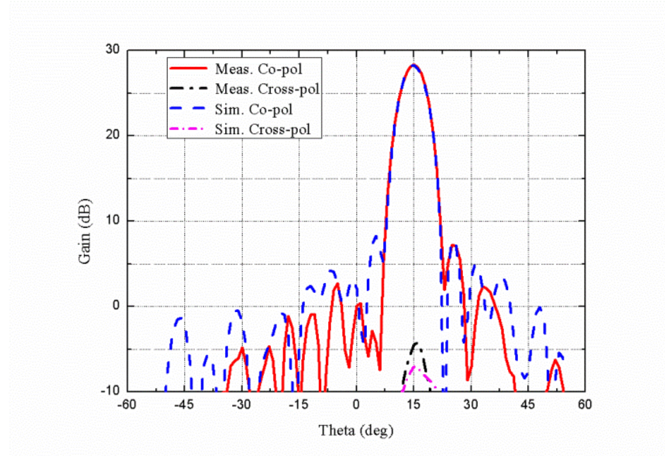


Fig. 6. Measured and simulated radiation patterns of the four-arm spiral element reflectarray for co-polar and cross-polar at 13.58GHz in H-plane.

The antenna simulated radiation characteristics are accomplished using the integral equation method of HFSS. The NSI planar near-field system is used to measure the performances of the fabricated prototype. The measured and simulated radiation patterns of the proposed reflectarray antenna for the co-polar and cross-polar at the center frequency of 13.58 GHz are shown in Fig. 5(E-plane) and Fig. 6 (H-plane). It can be observed that well agreement has been obtained between measured and simulated results. The measured gain level of 28.35 dB is obtained at 13.58 GHz with side lobe levels of -20 dB and -22 dB in E-plane and H-plane, respectively. The cross polarization levels are about -29 dB in E-plane and -33 dB in H-plane. Fig. 7 shows the measured and simulated results for the co-polar and cross-polar in φ = 30deg and φ = 45deg planes. It can be concluded that the cross polarization levels are below -27.5 dB in both φ = 30deg and φ = 45deg planes, which indicate that the antenna has a low cross polarization even in diagonal planes.

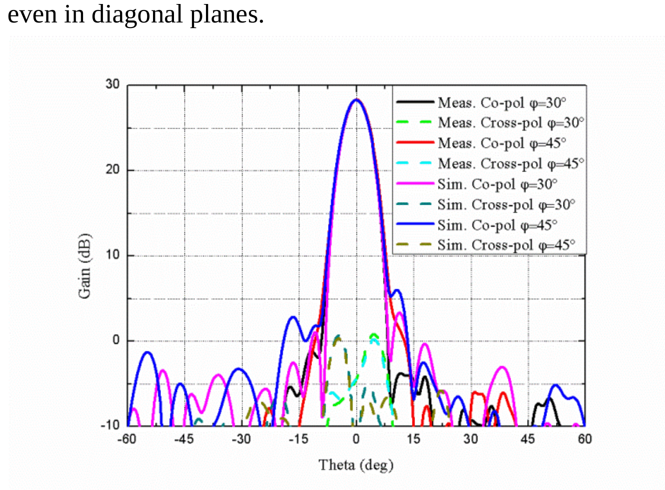


Fig. 7. Measured and simulated radiation patterns of the four-arm spiral element reflectarray for co-polar and cross-polar at 13.58GHz in φ =30deg and φ =45deg planes.

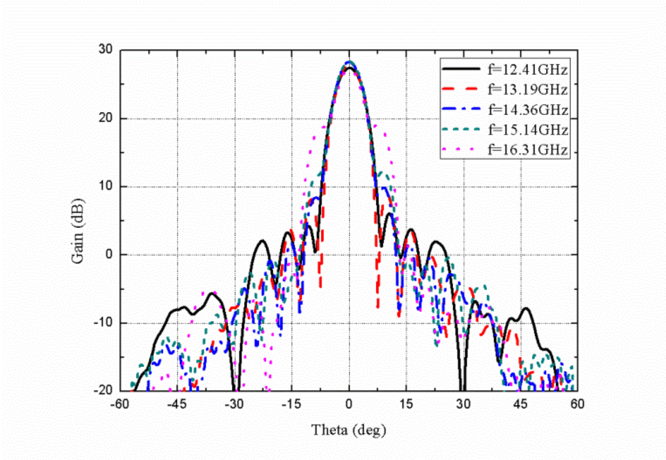


Fig. 8. Measured radiation patterns of the four-arm spiral element reflectarray in E-plane.

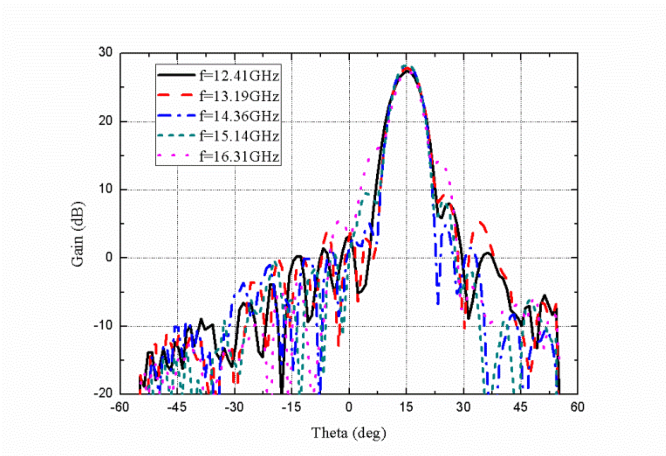


Fig. 9. Measured radiation patterns of the four-arm spiral element reflectarray in H-plane.

Fig. 8 and Fig. 9 show the measured radiation patterns of the four-arm element reflectarray at several frequencies (12.41GHz, 13.19GHz, 14.36GHz, 15.14GHz and 16.31GHz) in E-plane and H-plane, respectively. It can be concluded from Fig. 8 and Fig. 9 that the gain ripple is no more than 1 dB in the frequency range of 12.41-16.31GHz. Measured peak gains and efficiency of the reflectarray versus frequencies from 12.02 GHz to 17.09 GHz are shown in Fig. 10. The aperture efficiency ε is calculated using $\varepsilon = G_m / D_{ideal}$, $D_{ideal} = 4\pi A / \lambda_0^2$, where G_m is the measured gain, D_{ideal} is the ideal directivity, A is the aperture area of the reflectarray, and λ_0 is the free space wavelength. It can be observed from Fig. 10 that the 1-dB gain bandwidth and aperture efficiency reach 28.7% (12.41-16.31 GHz) and 60.2% at 13.58 GHz, respectively.

Table I lists the performance of the proposed four-arm spiral element reflectarray and some previous published works. It can be concluded that the four-arm spiral element reflectarray has the advantages of larger bandwidth compared to the single [11] and multi-layer [4, 5] reflectarrays.

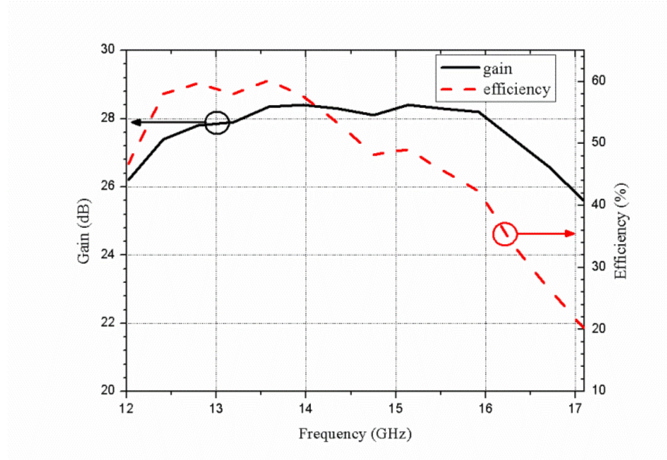


Fig. 10. Measured gain and efficiency of the four-arm spiral element reflectarray versus frequency.

TABLE I
COMPARISON OF THE PROPOSED REFLECTARRAY PERFORMANCE WITH PREVIOUS WORKS

Reference	this work	[4]	[5]	[6]	[11]
Frequency (GHz)	13.58	11.95	32	12	8.5
Gain (dB)	28.35	31	32.55	31.2	26.4
1-dB gain BW (%)	28.7	-	19.1	30	16.5
1.5-dB gain BW (%)	-	16.7	-	-	-
Efficiency (%)	60.2	52.5	-	-	59.2
Sidelobe level (dB)	< -20	-	-	< -20	< -20
Cross-pol level (dB)	< -27.5	≤ -25	-	-	< -25
Number of layers	1	2	2	1	1

IV. CONCLUSION

Four-arm Archimedes spiral elements are applied to design a broadband linearly polarized reflectarray antenna. The single-layer four-arm spiral element is optimized to produce large range linear reflection phase curve by varying the length of the arms. The parallel reflection phase curves for different frequencies imply that the four-arm spirals have wideband property as reflectarray elements. Measured results of the proposed reflectarray antenna show 28.7% 1-dB gain bandwidth and 60.2% aperture efficiency at 13.58GHz.

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